

Lunar Sample Science Today

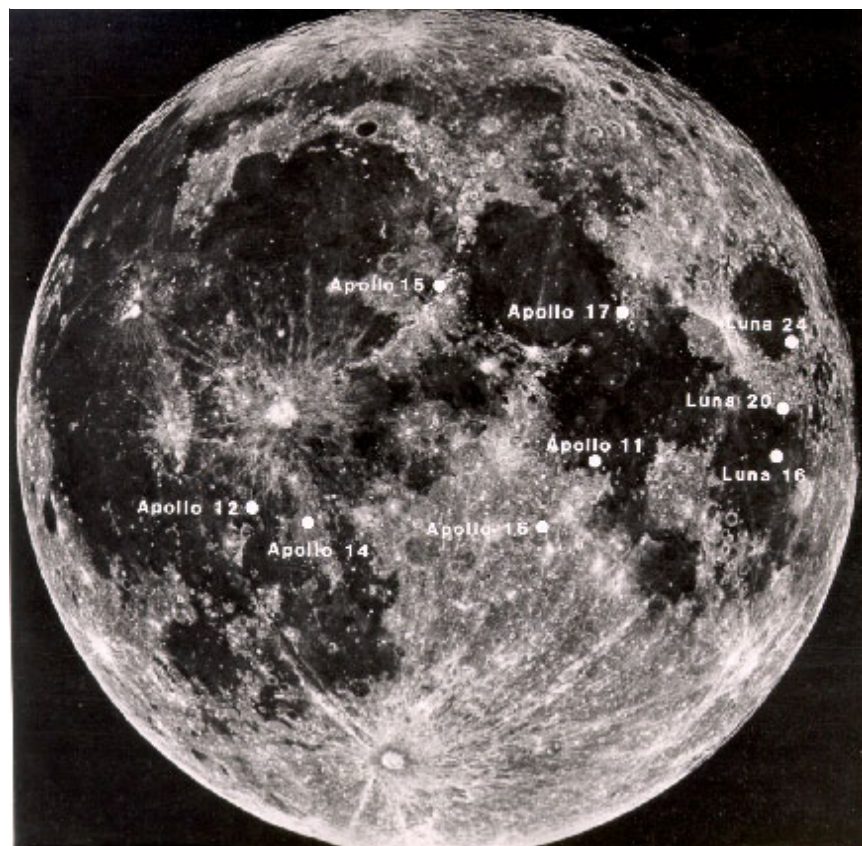


Figure 1. The Moon is divided into two basic physiographic regions: smooth maria and cratered highlands. The smooth maria fill the large circular basins and spill out onto low lying regions. They were sampled by Apollo 11, 12, 15 and 17 and Luna 16 and 24. The ejecta blankets of the large basins were sampled by Apollo 14, 15 and 17. The heavily cratered highlands were sampled by Apollo 16 and Luna 20. Note the great distances covered by rays from fresh craters. NASA photo no. 84-31673 (Lick Observatory)

The scientific rationale for lunar exploration is to establish the Moon's composition, internal structure, and history (or evolution). Before man walked on the Moon, scientists thought that the Moon was a relatively primitive (simple) object that would record the earliest history of the Solar System. Scientists also hoped that the lunar surface would contain a record of the Sun's history and of cosmic radiation, and they wanted to know if life had ever existed beyond that on Earth.

More than 50 U.S. and U.S.S.R. spacecraft have flown near or landed on the Moon. A total of 24 U.S. astronauts have observed the Moon in close proximity (3 astronauts went twice!) and 12 U.S. astronauts have walked on the lunar surface (including one geologist!). During 80 hours of surface activities, the astronauts carefully collected 382 kg of lunar samples (table 1).

In addition to the samples gathered from the six Apollo (U.S.) sites, we also have samples collected from the three Luna (U.S.S.R.) missions. Many exotic samples in the Apollo collection come from rays that extend as much as halfway around the Moon (fig. 1). Recently, numerous meteorites found in Antarctica and the Sahara desert have been shown to have originated on the Moon (Korotev 2003).

The scientific objectives and results of each Apollo mission are summarized in table II. From these missions, we learned that the Moon is not the simple, primitive object we once thought it to be, but, rather, a satellite that has been melted and differentiated twice in its history. The first melting occurred shortly after formation and apparently resulted in a Moon-wide magma ocean that cooled to form a thick crust of

Table I. – Lunar Sample Inventory

20 petrographic thin section sets (12 each)
 199 lunar educational disks (6 each)
 65 permanent and 15 traveling displays (~150 grams each)
 3 “touchstones”

By Mission	Weight	Number	EVA length	Distance
Apollo 11	21.5 kg	58	2.2 hr	0.5 km
Apollo 12	34.4	69	7.6	2.0
Apollo 13	aborted			
Apollo 14	42.3	227	9.2	3.4
Apollo 15	77.3	370	18.3	23.0
Apollo 16	95.7	731	20.1	20.7
Apollo 17	110.5	741	22.0	31.6
 Total Apollo	 382 kg	 2196	 89 hr	 81 kg
 Luna 16	 0.101 kg	 35 cm*		
Luna 20	0.050	27		
Luna 24	0.170	160		

Lunar Meteorites

Dhofar025	0.751 kg	ALH81005	0.031 kg
Dhofar081	0.4	Y791197	0.052
Dhofar026	0.4	Y983885	0.29
Dhofar302	0.2	Calcalong	0.019
Dhofar733	0.1	QUE94281	0.023
Dhofar489	0.035	SaU169	0.206
NWA482	1.015	Y793274	0.195
DaG400	1.425	EETA87521	0.084
DaG262	0.513	Y793169	0.006
DaG996	0.012	Asuka881757	0.442
MAC88104	0.724	NWA032	0.456
Y82192	0.712	Dhofar287	0.154
QUE93069	0.025	NWA773	0.633
YA1153		LAP02205	1.226
PCA02007	0.022		

By Type	weight	number
Soils	80 kg	167
Breccias	133	79 over 300 g each
Basalts	80	134 over 40 g each
Cores**	20	24 holes
Other	69	mostly small breccias
Meteorites	~10	29***

* The Luna samples were collected as small cores.

** Total length of Apollo cores is 15 meters (52 segments)

*** Number of lunar meteorites is increasing

Table II. – Summary of Findings from Apollo Missions

Apollo 11 Mare Tranquillitatis

Objective: sample relatively old mare surface

Results: Basalts high in Fe, Ti, approximately 3.7 BY

Conclusions: - water not important

- Maria are very old
- Maria are volcanic

Apollo 12 Oceanus Procellarum

Objective: sample relatively young mare; possible ray from Copernicus

Results: Basalts approximately 3.15 to 3.35 BY

Conclusions: - “Young” maria are very old!

- Copernicus may have formed approximately 0.9 BY ago
- Granite exists on the Moon!

Samples: 12002, 12005

Apollo 14 Fra Mauro

Objective: sample Imbrium ejecta, possibly deep material

Results: Variety of breccias, approximately 3.9 to 4.0 BY.
No deep material.

Conclusions: - Region is ejecta blanket of Imbrium basin

- Imbrium basin formed approximately 3.9 to 4.0 BY ago
- Trace-element-enriched rocks very abundant

Sample: 14305

Apollo 15 Hadley/Apennine

Objectives: sample mountainous rings of Imbrium basin, Hadley Rille and Imbrium Mare

Results: Mare basalts, approximately 3.2 BY; breccias, approximately 3.9 to 4.1 BY.

Conclusions: - Imbrium mare not produced by impact (took 600 MY to fill)

- Rille related to collapsed lava tube
- Highlands complex in composition

Sample: 15299

Apollo 16 Descartes

Objectives: sample highland plains

Results: Impact breccias approximately 3.8 to 4.2 BY

Conclusions: - Most flat highland areas formed by pooled impact ejecta; probably related to major multi-ringed basins

- Highlands are anorthositic

Samples: 60025, 65015

Apollo 17 Taurus-Littrow

Objectives: sample massifs from older basin (Serenitatis), flat valley plains between mountains and dark mantling (young volcanics?)

Results: Variety of breccias, approximately 4.0 BY; basalts (like Apollo 11), approximately 3.7 BY; volcanic glass approximately 3.5 BY

Conclusions: - Very young volcanism not evident

- Variety of breccias may represent older events
- No anorthosites!

Samples: 70017, 78235, 74220, 72275

anorthositic material. While cooling to form a solid body, parts of the interior melted again to form lava flows on the front side. The heat for the first melting comes from the terminal accretion; the heat for the second melting comes from the radioactive decay of K, U and Th in the interior. Much of this heat is brought to the surface with the extruded magma. Carefully refined computer models are now available with which to illustrate the thermal evolution of many planetary bodies, including that of the Earth.

From our study of lunar and meteorite samples, we have learned that different planets and moons have different chemical and isotopic signatures. For example, meteorites can be distinguished from samples of the Earth and the Moon by their high Ir and Au contents. Similarly, lunar samples can be distinguished from Earth samples by identifying their low Mn/Fe and K/U ratios. Small extraterrestrial samples have high He and D (^2H) contents. Martian samples have high $^{15}\text{N}/^{14}\text{N}$ ratios such as were found by the Viking missions to Mars. Using such signatures, scientists have shown that several meteorites found on the ice in Antarctica are actually lunar samples (Bogard 1983). A clay layer found at the Cretaceous-Tertiary boundary has been identified as having an extraterrestrial cause. Tektites,

once thought to have come from the Moon, have proven to be of terrestrial origin. Can chemical signatures like these be used to tell whether we have samples of other planets in meteorite collections?

We have discovered the bombardment history of the Moon by careful radiometric age dating of lunar samples (fig. 2). A surprising result was that most of the samples from the lunar highlands gave the same age; *i.e.*, 3900 to 4000 million years (Ryder 1990; Cohen 2001). This indicates that the Moon (and perhaps other planets as well) was subjected to an intensive period of bombardment late in its evolutionary history. The lack of intense cratering on the mare surface, which has been dated to as great an age as 3800 million years, means that this intense bombardment ended suddenly (a cataclysm). However, there appears to be no record of this cataclysmic bombardment in meteorites. Can we deduce from this the age of heavily cratered terrain either on Mars or Mercury?

A search for the oldest lunar rock is still ongoing but the identification of the most ancient sample has remained elusive (*see* Table V in the section of Plutonic Rocks). Perhaps it is the anorthosite sample 60025 included in this set. This research has continued for 30

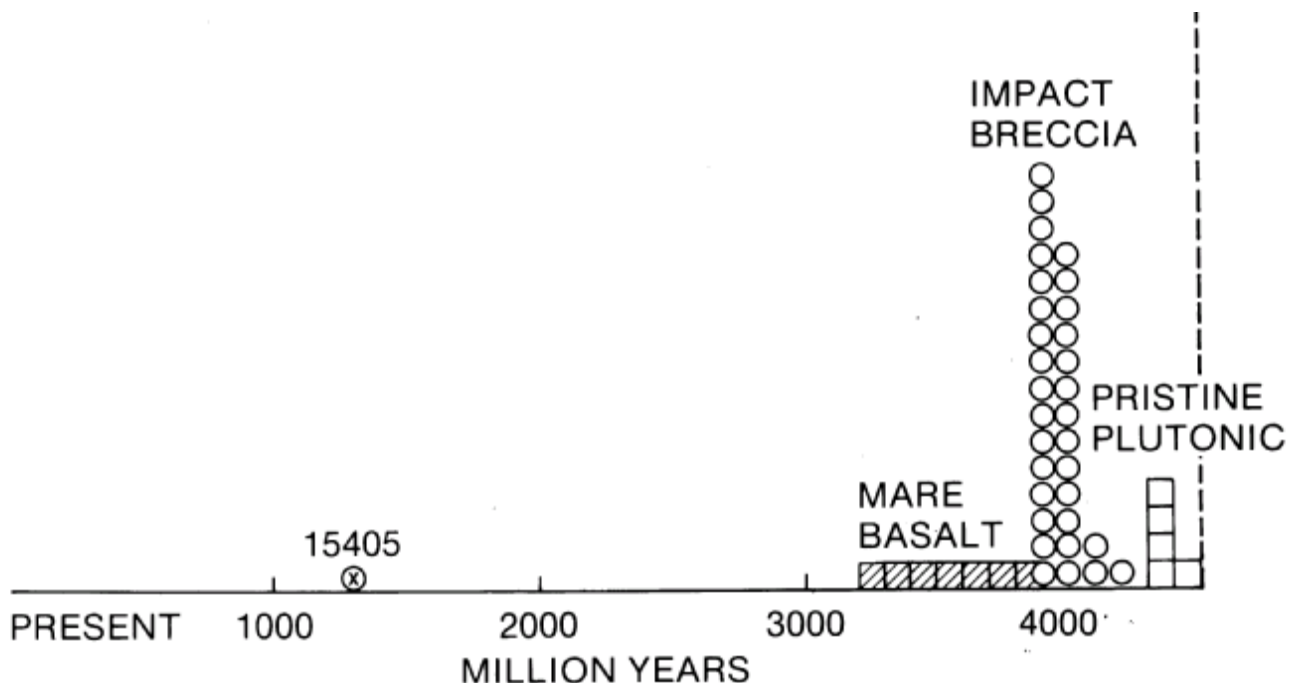


Figure 2. Cartoon. Impact breccias from the rims of large basins and the lunar highlands, all dated 3900-4000 million years. This has been termed the lunar cataclysm. Clasts of pristine lunar plutonic rocks are older. Mare basalts have ages spanning 3200-3900 million years. A few breccias are younger (e.g. sample 15405).

years after the last Apollo mission, because new instrumental techniques and revised procedures have had to be developed in order to date the oldest lunar rocks.

New laboratory techniques include Sm/Nd and Lu/Hf age dating, U/Th/Pb ion microprobe age dating, $^{39}\text{Ar}/^{40}\text{Ar}$ plateau age-dating, ferromagnetic resonance analysis (Is/FeO), and low-level neutron activation analysis for Au, Ir, and REE. These improvements have also directly benefited the study of terrestrial samples and several, well-equipped geochemical laboratories await additional extraterrestrial samples from other planetary bodies. Scientific studies of lunar samples currently in progress include; trace element partitioning between mineral phases and melt, initial isotopic ratios of lunar reservoirs as a function of time, analysis of volcanic glasses, dating of zircons and granite clasts, and modeling of Zr/Hf fractionation.

If we are clever enough to unravel the multiple processes which occur on the lunar surface, lunar samples might also reveal the history of the Sun and cosmic irradiation over hundreds of millions of years. This is because the lunar surface is directly exposed to micrometeorites, solar wind and cosmic radiation. A general conclusion which might be drawn from the study of solar-wind-implanted ions and tracks in soil grains is that the ancient Sun greatly resembled the modern Sun. The ratios of rare gases, hydrogen (H), and Fe in the Sun have remained almost constant.

Speculation and even some theory concerning the Moon's origin is discussed in Hartmann *et al.* 1986 and Canup and Righter 2000. Briefly, it is now thought that the Moon was formed from debris left over after a

large impact occurred on the Earth. This theory is mainly supported by the fact that lunar samples are found to have the same trend of oxygen isotopes as terrestrial samples.

About 50 meteorite fragments are now recognized as having a lunar origin (surprisingly none before 1982). Some of these are paired with one another such that there are about 29 different lunar meteorites (listed in Table I). They represent a great addition to the Apollo and Luna collections, because they provide a more statistically representative sampling of the lunar surface (Korotev 2003). One wonders whether these would have been recognized as having a lunar origin, if we did not have the Apollo and Lunar collections with which to compare!

Remote sensing of the lunar surface has continued with Earth-based telescopes, Galileo flyby (Belton *et al.* 1992), Clementine (*see* Science 266, 1994) and Lunar Prospector (Lawrence *et al.* 1998). These missions have discovered water in the regolith at the poles, confirmed the Th-rich region around Procellarum, mapped the Fe and Ti over the whole lunar surface and provided context with which to understand the rocks.

Lunar sample science is documented most fully in the Lunar Sourcebook (Heiken *et al.* 1991) and Lunar Samples (Papike *et al.* 1998). The books by Ross Taylor (1975, 1982) and Peter Cadogan (1981) provide great summaries of what was learned during Apollo. The web sites provided by Eric Jones and Kevin Clarke are highly recommended if one wants to revisit the excitement that was Apollo. Essays on various topics by Jeff Taylor are always worth reading and might be the best way for the student to get started (*see* References and some Links).